Engineering Structures 112 (2016) 274–286

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Tests and design of short steel tubes filled with rubberised concrete

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ARTICLE INFO

Article history:
Received 4 May 2015
Revised 26 November 2015
Accepted 12 January 2016
Available online 2 February 2016

Keywords:
Rubberised concrete (RuC)
Concrete filled steel tubes (CFST)
Experimental testing
Strength and ductility
Eurocode 4

ABSTRACT

An experimental investigation on the strength and ductility of short steel tubes filled with rubberised concrete (RuC), sourced from recycled scrap tyres, is presented in this paper. Firstly, a brief literature review on (i) concrete-filled steel tubes (CFST) and (ii) mechanical characterisation of rubberised concrete is presented. Then, the experimental investigation is described and test results are shown and discussed, namely, the assessment of (i) RuC and steel mechanical properties and (ii) RuCFST column structural properties. The influence of various parameters, such as the cross-section shape (square, rectangular, circular), steel grade, and concrete mix (standard concrete versus RuC), on the short column strength and ductility is analysed and discussed. Eurocode 4 is considered (i) to determine the strength of the tested columns and, in particular, (ii) to assess its applicability to RuCFST columns based on a comparison with the experimental results. The main conclusion of this research is that RuCFST short columns present higher ductility than those made of standard concrete, even though they also show lower strength. This improved ductility is noticeable in columns with circular sections, rather than in square and rectangular sections. From a practical viewpoint, this could be a major benefit for structures in seismic areas where energy dissipation is needed.

1. Introduction

Concrete filled steel tubes (CFST) are one of the most successful composite structural solutions available in the construction industry. In CFST columns, the steel tube acts as formwork and provides confinement to the concrete core, improving its strength and ductility, whereas the concrete core reduces the steel tube sensitivity to local buckling. Regarding the steel tube design, its target (maximum) strength may be achieved in two different ways: (i) for a given (fixed) yield stress, by increasing the amount of steel (e.g. increase the thickness) or (ii) for a fixed tube diameter and thickness, by increasing its steel grade (yield stress). Nowadays, with the advent of high-strength steels, the latter solution might be adopted more frequently than the former. For the same level of strength, the designer can choose between adopting thinner tubes made of high strength steel or thicker tubes made of standard steel grades. Notwithstanding the fact that this option may have negligible impact in terms of strength, it should have a significant influence on the ductility of the tube. In case of thin (and very thin) steel tubes, the susceptibility to local buckling increases and, consequently, the ductility of the tube decreases and its ability to dissipate energy from dynamic actions also decreases. Therefore, if very thin tubes are used in CFST solutions, special attention should be devoted to their ductility. It has been shown that if made of high-strength steel and/or high-performance concrete, CFST columns exhibit low ductility, which is not desirable, for instance, is seismic resistant structures.

Several works have focused on the influence of using high-performance materials in CFST columns. Liu [1] performed experimental investigations on the strength and ductility of square (SHS) and rectangular (RHS) high-strength CFST columns (sectional aspect ratios between 1.0 and 2.0). These shapes resulted from the welding of four flat steel plates, with slenderness between 30 and 50, and yield stress $f_y = 495$ MPa. Two high-strength concrete cores were also investigated ($f_c = 60$ MPa and $f_c = 89$ MPa). Comparison was made between experimental strengths (P_{Exp}) and ultimate loads predicted (P_{Pred}) by means of ACI [2], AISC [3], and EC4 [4]. The author pointed out that EC4 provides better strength estimates (EC4 – $P_{EC4}/P_{Exp} = 0.99$; ACI – $P_{ACI}/P_{Exp} = 0.92$; AISC – $P_{AISC}/P_{Exp} = 0.90$) and that RHS with aspect ratio higher than 2.0 are not recommended for structural applications.

Regarding the use of high performance steel, Uy [5] investigated the behaviour of CFST columns with high strength steel (HSS) ($f_y = 690$ MPa) and stainless steel (SS) ($f_y = 340$ MPa). Even though

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http://dx.doi.org/10.1016/j.engstruct.2016.01.018
0141-0296/

SS may provide higher ductility when used in CFST columns, Uy [5] showed that the initial cost of SS (about five times more than carbon steel), and the difficulty of classifying the plate slenderness of SS compressed elements due to its highly non-linear stress–strain curve and strain hardening, were still complex challenges that require further research.

Besides the influence of the steel tube, the concrete core also plays an important role on the performance of CFST columns. Ellobody et al. [6] numerically assessed the influence of the concrete core on the strength and ductility of circular (CHS) CFST columns tested by Giakoumelis and Lam [7] and Sakino et al. [8]. Columns with concrete compressive strengths ranging from $f_c = 30$ MPa to $f_c = 110$ MPa (from cube samples) and steel yield stresses varying between $f_y = 343$ MPa and $f_y = 525$ MPa were modelled. Good agreement was found between the models and the experimental data and the authors found out that CFST column ductility decreases as the concrete strength increases. Ellobody et al. [6] also compared their numerical strengths (P_{Num}) with predicted ultimate loads (P_{Pred}) and concluded that ACI [2] and AS/NZS [9,10] provide conservative estimates ($P_{ACI/AS/NZS}/P_{Num} = 0.81$) while EC4 [4] estimates are mostly non-conservative ($P_{EC4}/P_{Num} = 1.11$). Regarding CFST columns with SHS and RHS, Ellobody and Young [11] also concluded that CFST ductility decreases as the concrete core strength increases (f_c between 30 MPa and 110 MPa). ACI [2] and AS/NZS [9,10] were found to provide conservative predictions of the collapse strength ($P_{ACI/AS/NZS}/P_{Num} = 0.93$) while EC4 [4] was found to lead to accurate estimates of CFST strength ($P_{EC4}/P_{Num} = 1.00$).

Today, one of the most problematical issues concerning sustainability and ecology is recycling scrap tyres. Many companies are working towards putting together sustainable programs to create additional ways for tyres to be reused instead of dumped into landfills. One possible solution is to use rubber tyre particles as aggregates in concrete. Rubberised concrete (RuC) is a type of concrete in which natural aggregates are partially replaced by rubber aggregates, which can be fabricated from tyres via a cryogenic process or a mechanical process. Additionally, this replacement of natural aggregates by rubber particles also implies less extraction of natural resources, reducing the environmental impact.

During the last three decades, several authors have investigated RuC. During the 90s, Topçu [12] was one of the pioneers in the study of the mechanical properties of RuC compositions with 15%, 30% and 45% replacements of total natural aggregates, in volume, of a standard concrete (NC) mixture, separately, with fine and coarse tyre rubber aggregates. The author reported (i) reductions higher than 50% in cubic and cylindrical compressive strengths for 45% fine rubber replacement and (ii) up to 80% reductions in cubic strengths, in compositions with 45% coarse rubber aggregates, compared to that of NC. However, increases of ductility of RuC relative to that of NC were reported and recommendations were made for its use in applications where energy dissipation capacity is required and high strength is not necessary.

In agreement with the conclusions drawn by Topçu [12], Li et al. [13] concluded that most mechanical and physical properties of RuC are lower than those of NC, the exception being its improved ductility. These authors studied a RuC in which 33% of a NC composition's sand volume was replaced with 2.5 mm maximum size rubber particles obtained by a cryogenic grinding process. In order to improve the adherence of the rubber particles to the concrete matrix, Li et al. [13] studied the properties of two additional RuC mixes by pre-saturating the rubber particles with (i) cement paste and (ii) methocel cellulose ether. The RuC composition with the cement paste pre-saturated rubber particles was the one that presented the best mechanical performance, especially concerning compressive strengths. In order to evaluate the RuC's response to dynamic actions, Li et al. [13] performed base acceleration tests on specimens containing both RuC and NC and NC only. These authors concluded that the use of RuC decreases the natural frequency of a structural element and provides an increase of its damping ratio. Later, Zheng et al. [14] also observed that RuC contributes to an increase of up to 75% (fine replacement) and 144% (coarse replacement) in the damping ratio values, compared to those of NC.

Since the (i) rubber particle size, (ii) process of production (mechanical or cryogenic), (iii) replacement ratio and (iv) size of the rubber particles (fine, coarse or total) replacing natural aggregates may play a key role on the properties of RuC, Valadares et al. [15] studied the mechanical properties of RuC by extensively varying the aforementioned parameters. Therefore, the authors studied 12 RuC mixes resulting from the replacement of the natural aggregates volume with rubber particles in percentages of 5%, 10% and 15% in (i) fines only, (ii) coarse only and (iii) simultaneously in fine and coarse fractions of a NC composition. Additionally, for the fine fraction replacement (also for 5%, 10% and 15%), both cryogenic and mechanically ground rubber particles were studied. In opposition to the conclusion drawn by Topçu [12], Valadares et al. [15] reported larger decreases in the mechanical properties of RuC when the natural aggregates replacement with rubber particles was made in the fines fraction, concluding also that both cryogenic and mechanically ground fine rubber particles led to similar mechanical performances. RuC mixes with simultaneous replacement of fine and coarse particles presented moderate results and RuC mixes with coarse natural aggregates with coarse rubber particles replacement presented better mechanical performances, compared to other RuC mixes.

Summing up, even though the aforementioned studies present a widespread set of parameters regarding RuC compositions, overall conclusions point out that RuC has lower mechanical properties than NC: lower Young's modulus and lower (compressive and tensile) strength. This is a natural consequence of the low strength and stiffness of rubber particles, when compared with natural aggregates. On the other hand, RuC is lighter than NC because rubber particles have lower density than natural aggregates. Therefore, it should be expected that structural eigenfrequencies should not vary too much between NC and RuC because both stiffness and mass decrease. Additionally, RuC also exhibits an ultimate strain larger than NC, which is a valuable property when ductility and energy dissipation are required.

Aiming at developing high seismic performance CFST columns, in which ductility and energy dissipation capacity are sought, rubberised concrete filled steel tubes (RuCFST) are introduced (Fig. 1). Hence, one can take advantage of both the structural performance of the composite solution and the mechanical capabilities of RuC that are reported to improve the ductility and energy dissipation capacity compared to those of NC. Additionally, the insertion of RuC inside the steel tube mitigates the losses of strength, stiffness and durability performance [16] presented by this material. Furthermore, its use also allows the construction industry to tackle the sustainability problem concerning the destination of end-of-life tyres.

Following the previous assertions, the main objective of this paper is to present an experimental investigation on the strength and ductility of square, rectangular and circular RuCFST short columns – similar CFST columns made of NC are also considered for comparison purposes. Firstly, the experimental programme to assess the steel and concrete (RuC and NC) properties is presented. Then, the setup to test the CFST and RuCFST columns under monotonic pure compression is described and the experimental results are presented and discussed, with emphasis on the strength and ductility. Finally, EC4 [17] and EC3 [18–20] design provisions are described, experimental (P_{Exp}) and predicted (P_{EC4}) ultimate strengths are compared and conclusions are drawn.